

NET CIRCULAR POLARIZATION OF SUNSPOT PENUMBRAE - A VERSATILE TOOL FOR DIAGNOSING MAGNETIC FIELD STRUCTURE

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ABSTRACT

Sunspot penumbrae harbor highly structured magnetic fields and flows. The moving flux tube model (Schlichenmaier et al. 1998) offers an explanation for several observed phenomena, e.g. the Evershed effect and bright penumbral grains. In this work, we present a generalized 3D model that embeds an arbitrarily shaped flux tube in a stratified magnetized atmosphere. The new model is a versatile tool to calculate the spectral signature of flux tubes in the penumbra and especially make predictions about the flow speed and tube inclination from observed maps of the net circular polarization (NCP). As a first result, we find that the inclination of downflows in the outer penumbra must be shallower than approximately 15° .

1. INTRODUCTION

Spectral line profiles in the penumbra are characterized by line shifts and line asymmetries of their intensity (Stokes-I) as well as in polarized light (Stokes Q, U, and V). A suitable measure of the asymmetry of Stokes-V profiles is the area asymmetry or *net circular polarization*, \mathcal{N} , of a spectral line, which we define as

$$\mathcal{N} \equiv \int_{\delta\lambda} V(\lambda) d\lambda, \quad (1)$$

where the interval of integration, $\delta\lambda$, encompasses the whole line profile. This quantity has the advantage that it is independent of the spatial resolution of the observations since a convolution of a line profile with a Gaussian preserves its area. The first measurements of the net circular polarization in sunspots were reported by Illing et al. (1975), and Auer & Heasley (1978) showed that these observations could be explained by assuming macroscopic velocity fields. Furthermore, they proved that velocity gradients are a necessary *and* sufficient condition to produce a NCP.

The advent of modern polarimeters like the Tenerife Infrared Polarimeter (TIP) and the Polarimetric Littrow Spectrograph (POLIS) at the Vacuum Tower Telescope (VTT) on Tenerife has brought new challenges to observers as well as theoreticians. It is now possible to routinely obtain maps of the full Stokes vector for a whole sunspot. This facilitates the study of spectral signatures of magnetic flux tubes in the penumbra by analysis of maps of the NCP.

So far, the spectral synthesis has been limited to atmospheric models based on snapshots of the moving tube model simulations by Schlichenmaier et al. (1998) and to configurations in a two-dimensional plane (“slab models”). Such slab models have been used earlier by Solanki & Montavon (1993), Sánchez Almeida et al. (1996) and Martínez Pillet (2000) and lead to the picture of the “un-combed” penumbra: Approximately horizontal magnetic flux tubes are embedded in a more inclined background field which is at rest. The sharp gradient or even discontinuity of the velocity of the plasma between the inside the tube and the static surroundings result in the observed NCP. Two-dimensional models succeeded in reproducing the observed NCP and its center-to-limb variation. However, these models are limited to the few geometric cases where a flux tube is exactly aligned with the line-of-sight and do not give any information about the NCP at different positions within the penumbra.

We showed (Müller et al. 2002; Schlichenmaier et al. 2002) that a wealth of additional information is contained in NCP maps that can be retrieved with the help of a three-dimensional model. Jumps in the azimuth of the magnetic field (as measured in the observer’s coordinate system) lead to a characteristic pattern of the NCP within the penumbra. Specifically, it was shown that the apparent symmetry within the spot is broken due to the following fact: The jumps in the magnetic field azimuth are different for two locations which are symmetrically located in the spot with respect to the “line-of-symmetry” (Fig. 1).

The impact of this geometric effect on the NCP strongly varies between spectral lines at different wavelengths. A comparison of the NCP of different spectral lines can thus be used to diagnose the magnetic field inclination and orientation of flow channels in the penumbra.

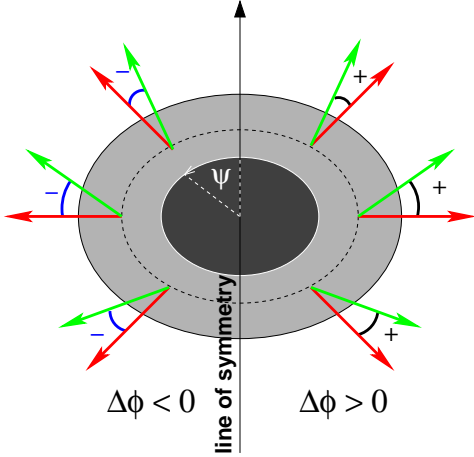


Figure 1. Pictorial representation of the difference in azimuth, $\Delta\phi(\psi)$, between the magnetic field vector inside a flux tube (red arrows) and that of the background field (green arrows). The tubes are nearly horizontal, while the field vector of the background has a steeper inclination, but is also in the plane spanned by the spot axis and the flux tube axis.

As an example, we consider the two iron lines FeI 1564.8 nm and FeI 630.25 nm. Both lines are Zeeman triplets and have similar Landé factors of $g=3$ and $g=2.5$, respectively, and differ mainly in wavelength. It turns out that the infrared line (FeI 1564.8 nm) is far more susceptible to the symmetry breaking than the visible line (for details, cf. Müller et al. 2002).

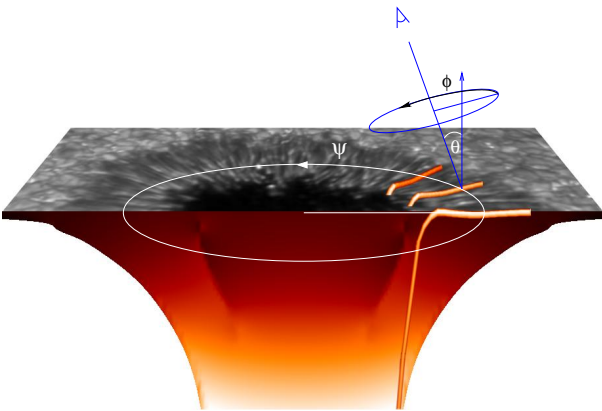


Figure 2. Magnetic flux tubes in the penumbra. For a given heliocentric angle θ , the azimuth ϕ and the inclination γ of the magnetic field vary with the location of the flux tube in the sunspot, characterized by the spot angle ψ .

2. THE VTUBE MODEL

In order to gain a better understanding of the different factors that determine the NCP and its spatial variation within the penumbra, we constructed a 3D geometric model (VTUBE) of a magnetic flux tube embedded in a background atmosphere. This model serves as the frontend for the radiative transfer code DIAMAG (Grossmann-Doerth 1994). Combining the two, we can generate synthetic NCP maps for any desired axisymmetric magnetic field configuration and arbitrary flux tube properties. The model has been built to offer a high degree of versatility, e.g. the option to calculate several parallel rays along the line-of-sight which intersect the tube at different locations. One can then average over these rays to model observations of flux tubes at different spatial resolutions and for different magnetic filling factors of the atmosphere. Furthermore, we can also take into account radial variations of the physical properties of the flux tube. Doing so, one can e.g. model the interface between the flux tube and its surroundings.

Figure 2 shows the relevant angles which occur in the model. For a given heliocentric angle θ , the azimuth ϕ and the inclination γ of the magnetic field vary with the location of the flux tube in the sunspot, characterized by the spot angle ψ . The sketch in Fig. 3 additionally shows the tube inclination angle, α . The VTUBE model will be described in detail in a forthcoming paper (Müller et al. 2006). For the calculations presented in this contribution, no averaging over parallel rays was performed, and the physical quantities were kept constant along the flux tube radius (thin flux tube approximation).

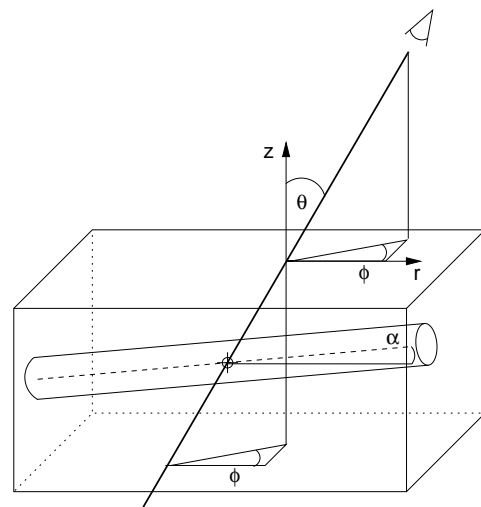


Figure 3. Embedding a flux tube in a background atmosphere. The line-of-sight is defined by the magnetic field's inclination θ and azimuth ϕ . The local inclination of the flux tube is given by the angle α .

2.1. Building a realization of the model

The following steps are performed to assemble a realization of the penumbral flux tube model:

1. In the first step, the background magnetic field of the penumbra, $\mathbf{B}(r, z)$, is prescribed.
2. The flux tube axis is defined by a polygon or spline function.
3. The physical properties of the flux tube are defined and then interpolated along the flux tube axis.
4. A functional dependence of the physical properties on the radius of the flux tube can be prescribed, e.g. to model the cooling of a flux tube.
5. The viewing angle is defined by specifying the heliocentric angle and the location of the line-of-sight.
6. The spectral line profiles are calculated.

3. FIRST RESULTS

Figure 4 shows a first comparison between NCP maps from observations, the old moving tube model, the new VTUBE model and a recent 2-component Stokes inversion of observations with the TIP and POLIS instruments (Beck 2006). The upper row shows maps of the NCP of the Fe I 1564.8 nm infrared line, the bottom row shows maps of the NCP of the Fe I 630.25 nm visible line. The observations (left column) indicate that the NCP distribution around the penumbra has two maxima and two minima in the infrared and is roughly antisymmetric with respect to the line-of-symmetry (line from spot center to disk center, indicated by a red arrow). The Müller et al. (2002) model (second column from the left) is able to reproduce this fundamental difference. Since it is limited, however, to given snapshots of the MHD model, we extended the model (VTUBE, third column from the left). The displayed maps are based on a velocity variation along the flux tubes that has been inferred from observations by Stokes inversion (Beck 2006). The last column shows results from pointwise Stokes inversion as an independent check. The arrows point towards disk center. The absolute magnitude of the NCP is higher for the synthetic maps than for the observations since a filling factor of unity is assumed, i.e. each line of sight is passing through the center of a magnetic flux tube.

These results are very promising and have stimulated further modeling efforts. One open question, e.g., is whether magnetic flux tubes dive back down into lower atmospheric layers in the outer penumbra and, if so, at which angle. Figure 5 shows the variation of the NCP along a circular cut in the outer penumbra for the infrared line Fe I 1564.8 nm. For tube inclination angles of $\alpha \geq -15^\circ$, the curve has two pronounced maxima and minima, while

there is only one of each for smaller angles, i.e. more vertical downflows. There are two points to be made here. The first one is that the different shapes of the curves can be explained by applying the simplified analytical model of (Landolfi & Landi Degl’Innocenti 1996, see Müller et al. (2002) for details). The NCP is proportional to $-v_{LOS} \cdot \sin(2\Delta\phi)$ where v_{LOS} is the line-of-sight velocity and $\Delta\phi$ is the jump in the azimuth of the magnetic field between the flux tube and the background atmosphere. The second point is that the observed azimuthal variations of the NCP in the infrared line always show two maxima and two minima. This rules out flux tubes that descend at an angle steeper than about $\alpha < -15^\circ$.

4. SUMMARY

We have presented a generalized geometrical model that embeds an arbitrarily shaped flux tube in a stratified magnetized atmosphere. The new model is a versatile tool to calculate the spectral signature of flux tubes in the penumbra and especially make predictions about the flow speed and tube inclination from observed maps of the net circular polarization. From the first applications of the new model, we find that the inclination of downflows in the outer penumbra must be shallower than approx. 15° . More details about the model and further results will be published in Müller et al. (2006).

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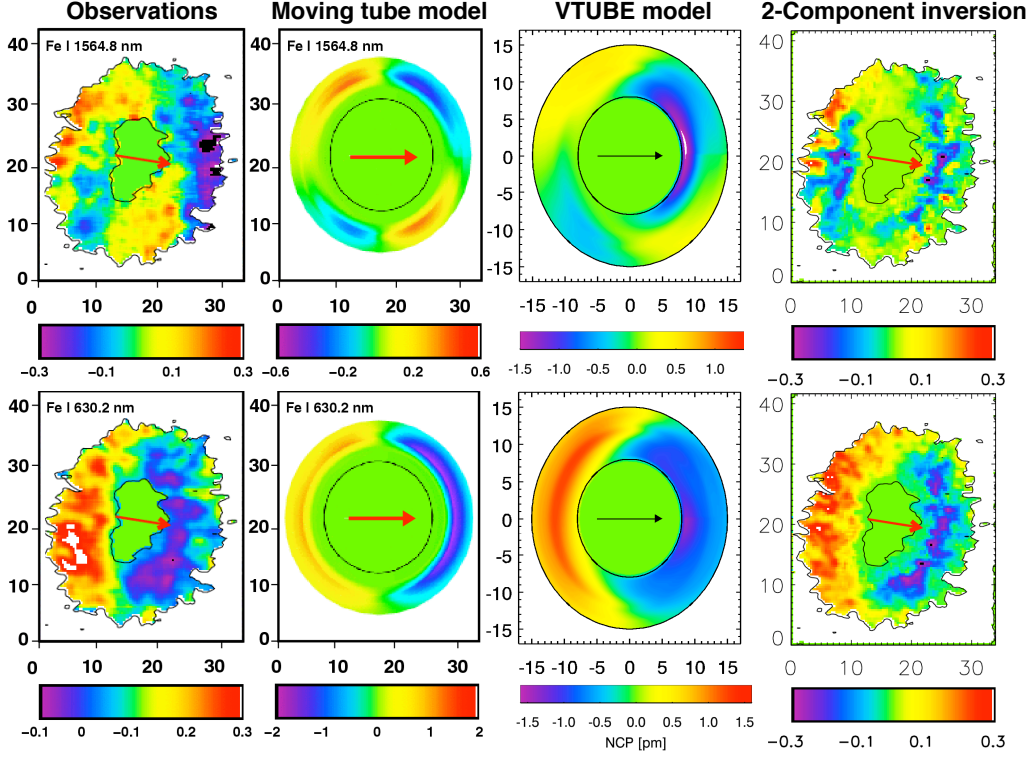


Figure 4. Maps of net circular polarization (NCP) for an heliocentric angle of $\theta = 30^\circ$. Upper row: infrared line (Fe I 1564.8 nm), bottom row: visible line (Fe I 630.25 nm). Columns from left to right: observations (VTT, Tenerife), NCP maps synthesized from the moving tube model, and maps from the new generalized model. The last column shows results from pointwise Stokes inversion as an independent check. The arrows point towards disk center. The absolute magnitude of the NCP is higher for the synthetic maps than for the observations since a filling factor of unity is assumed.

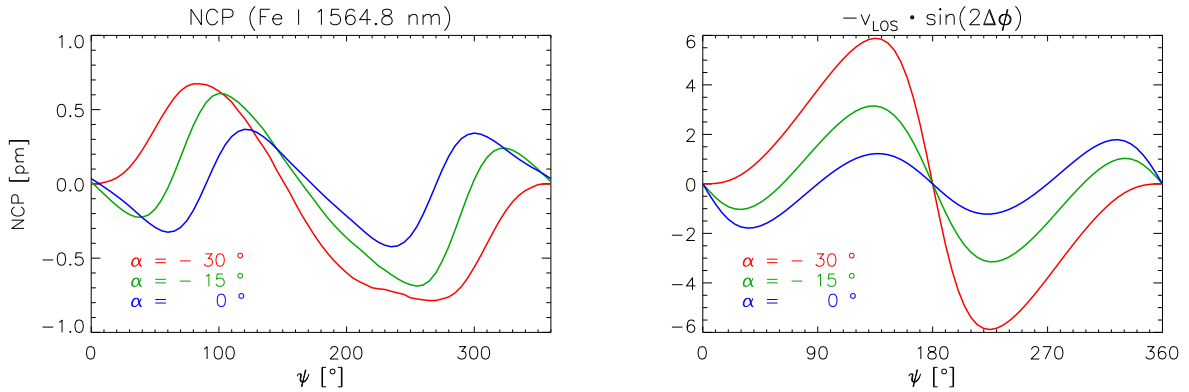


Figure 5. Variation of the NCP along a circular cut in the outer penumbra for the infrared line Fe I 1564.8 nm. For tube inclination angles of $\alpha \geq -15^\circ$, the curve has two pronounced maxima and minima, while there is only one of each for smaller angles, i.e. more vertical downflows. The different shapes of the curves can be approximated by the term $-v_{LOS} \cdot \sin(2\Delta\phi)$ where v_{LOS} is the line-of-sight velocity and $\Delta\phi$ is the jump in the azimuth of the magnetic field between the flux tube and the background atmosphere.